Scientific Research Publishing

Open Journal of Modern Hydrology, 2026, 16(1), 84-98
https://www.scirp.org/journal/ojmh
ISSN Online: 2163-0496
ISSN Print: 2163-0461

Key Mechanisms Leading to the East-West Asymmetric Impacts of Convectively Coupled Kelvin Waves on the West African Monsoon

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How to cite this paper: Diakhaté, M. and Dieng, A.L. (2026) Key Mechanisms Leading to the East-West Asymmetric Impacts of Convectively Coupled Kelvin Waves on the West African Monsoon. *Open Journal of Modern Hydrology*, **16**, 84-98.
https://doi.org/10.4236/ojmh.2026.161006

Received: October 30, 2025
Accepted: December 25, 2025
Published: January 28, 2026

Abstract

Convectively coupled Kelvin waves (CCKWs) are among the most influential sources of synoptic-to-intraseasonal variability affecting the West African monsoon. Yet, how their impacts differ across the West Africa and why rainfall transitions occur earlier in some regions than others remain poorly documented. Using daily observations and reanalysis fields for 1981-2024, this study investigates Kelvin-wave modulation of West African rainfall during July-September, focusing on the contrasting responses of eastern and western West Africa. Composite analyses reveal a coherent wet (phase 2) and dry (phase 6) structure, but with markedly sharper and earlier transitions in the east. The Intertropical Discontinuity and vertical wind shear show little longitudinal dependence, indicating that surface and mesoscale factors do not drive the asymmetry. Instead, the key mechanism originates from the vertical generation of humidity anomalies by Kelvin-wave-induced subsidence and ascent. Eastern West Africa exhibits deeper mid-level drying during the wet-to-dry transition and earlier moistening during the dry-to-wet transition, producing stronger humidity anomalies q'. These anomalies are subsequently redistributed horizontally by the mean monsoon flow, yielding earlier sign reversals in the flux term $\overline{u}q'$. Western regions, with a weaker vertical response, transition more gradually. This integrated vertical-horizontal mechanism explains the spatial heterogeneity of Kelvin-wave impacts and highlights the need for forecasting systems to resolve regional differences in vertical humidity sensitivity.

Keywords

Convectively Coupled Kelvin Waves, West African Monsoon, Moisture Flux and Humidity Anomalies, Intraseasonal Variability, Zonal Rainfall Asymmetry

1. Introduction

Rainfall variability across West tropical Africa arises from multiple interacting dynamical processes that span synoptic to intraseasonal timescales. This multiscale structure, which shapes both the timing and intensity of rainfall during the boreal summer monsoon, is traditionally decomposed into three dominant regimes: high-frequency disturbances with periods shorter than 10 days; short intraseasonal oscillations (10 - 25 days); and longer intraseasonal fluctuations up to 60 days [1]. On the short intraseasonal timescale, two dominant regional modes have been identified: the quasi-biweekly zonal dipole (QBZD [2]) and the *Sahel mode* [3], the latter being characterized by a meridional displacement of rainfall anomalies between the Guinean coast and the Sahel, associated with large-scale monsoon circulation variability. These intraseasonal modes do not occur in isolation but reflect the projection of larger-scale tropical disturbances onto the West African monsoon system. In particular, their temporal and spatial characteristics suggest a close connection with equatorial wave dynamics and regional thermodynamic forcings. The former is frequently associated with eastward-propagating convectively coupled Kelvin waves (CCKWs), whereas the latter tends to reflect the influence of equatorial Rossby activity [4]. Superimposed on these wave signals, fluctuations in the Saharan heat low also contribute significantly to rainfall modulation within the 10 - 25-day range [5] [6].

CCKWs are among the most coherent forms of synoptic-scale variability in the tropics. They propagate eastward at 10 - 20 $m \cdot s^{-1}$, exhibit horizontal and vertical structures consistent with equatorial Kelvin modes, and maintain a tight coupling between deep convection and dynamically coherent circulation anomalies [7] [8]. Although much of the foundational literature has focused on the Indo-Pacific warm pool (where Kelvin wave activity is strongest and most frequent [9]-[11]), recent work has highlighted their downstream influence as they traverse the African continent. [12] showed that Kelvin waves can alter several components of the West African monsoon system, while [13] demonstrated their capacity to modulate extreme rainfall events over the central Sahel, contributing independently to an 8% - 10% increase in the likelihood of heavy precipitation.

Understanding such processes is particularly critical in West Africa, where rainfall fluctuations have immediate societal consequences. More than 96% of cultivated land in sub-Saharan Africa relies exclusively on rainfall [14], and anomalies in the timing and intensity of monsoon precipitation strongly affect food security, water management, and disaster preparedness [15]. Yet global numerical weather prediction systems continue to struggle with short-range rainfall forecasts in this region [16], underscoring the need for improved characterization of the underlying dynamical drivers, especially those associated with tropical waves.

Several recent studies have examined Kelvin wave influences in Africa, but few have specifically focused on their behavior and dynamical impacts during July-August-September (JAS) [17], for instance, investigated April conditions near the equator and did not analyze the core monsoon months. [12] provided a comprehensive description of tropical wave impacts on monsoon dynamics but did not isolate regional asymmetries or transition mechanisms. Meanwhile, [13] emphasized Kelvin-wave contributions to extreme rainfall but did not explore the spatial heterogeneity of their impacts.

Building on these foundations, the present study addresses a gap in understanding: how Kelvin waves modulate rainfall specifically during JAS over West Africa, and why their impacts exhibit a pronounced east-west asymmetry. Observational evidence presented here shows that the transition between wet and dry Kelvin wave phases occurs faster and more abruptly in eastern than in western West Africa, suggesting differences in dynamical sensitivity that remain undocumented in the literature. This article is organized as follows. Section 2 presents the observational datasets, reanalysis fields, and methodological framework used to extract Kelvin wave activity and construct the composite analyses, including the detailed formulation of the moisture-flux budget. Section 3 describes the modulation of the West African rainfall across the eight Kelvin-wave phases and documents the east-west asymmetry that emerges during the transition periods. It also investigates the underlying dynamical mechanisms through diagnostics of the ITD position, vertical wind shear, horizontal moisture transport, and vertical structures of humidity and vertical velocity. Section 4 discusses the broader implications of these findings for monsoon dynamics and subseasonal predictability. Finally, Section 5 summarizes the main conclusions and outlines perspectives for future work.

2. Data and Methods

This study combines satellite-derived rainfall products, convection proxies, and atmospheric reanalyses to examine the dynamical influence of CCKW on West African monsoon rainfall during July-August-September (JAS). Daily precipitation is obtained from the CHIRPS dataset at 0.25˚ resolution. This product blends infrared satellite estimates with in situ observations and provides one of the most reliable long-term records for monitoring rainfall variability and extreme events over West Africa. Deep convection is characterized using daily Outgoing Longwave Radiation (OLR) from NOAA, which serves as the primary tracer for isolating Kelvin wave activity. Atmospheric fields, including horizontal winds, vertical velocity, and specific humidity, are extracted from ERA5 at the same spatial resolution. The ERA5 fields are used to diagnose the circulation anomalies, moisture transport, vertical structure of humidity, and dynamical signatures associated with Kelvin wave propagation.

Kelvin waves are identified through zonal wavenumber-frequency filtering of

OLR following the methodology of [8]. The filter retains eastward-propagating components with zonal wavenumbers 1 to 14, and periods between 2 and 17 days, ensuring that the dominant CCKW spectrum is captured. The filtered OLR is normalized and its temporal oscillation at each longitude is used to define an eight-phase Kelvin-wave life cycle. Phase 2 represents the peak convective stage of the wave, while phase 6 corresponds to the suppressed convective stage. The intermediate phases form two transition sequences: a wet-to-dry evolution (phases 3 - 4) and a dry-to-wet evolution (phases 7 - 8). These phases serve as the temporal framework for all composite analyses presented in this study.

Composite anomalies are constructed by averaging all days corresponding to a given Kelvin-wave phase and subtracting the JAS climatology. Rainfall, OLR, low-level winds, vertical shear, and humidity fields are composited in this manner. The meridional position of the Intertropical Discontinuity (ITD) is computed following the approach of [12], using the 15 $g \cdot kg^{-1}$ specific humidity isoline at 925 hPa as a robust indicator of the low-level moist-dry air interface. To highlight the east-west differences in Kelvin-wave impacts, two regions are defined: Western West Africa (WWA, 5˚W - 5˚E/5˚ - 15˚N) and Eastern West Africa (EWA, 15˚ - 22˚E/0˚ - 10˚N), each covering a longitudinal band of comparable area across West Africa. All regional diagnostics are computed separately for these subdomains.

To investigate how Kelvin waves modulate the moisture environment over West Africa, we compute a moisture flux budget based on the horizontal moisture flux vector, defined as:

$$F = uq$$

where q is specific humidity and u is the horizontal wind vector on a given pressure level. Unlike classical moisture-budget studies that evaluate the divergence of this flux to diagnose sources and sinks of moisture, our analysis focuses exclusively on the structure of the flux itself and its anomalies across Kelvin-wave phases.

To interpret the modulation of moisture transport, the total flux is decomposed into mean and anomaly components:

$$u = \overline{u} + u', \quad q = \overline{q} + q'$$

Substituting into the total flux gives:

$$\mathrm{F} = \left(\overline{u}\overline{q}\right) + \left(u'\overline{q}\right) + \left(\overline{u}q'\right) + \left(u'q'\right)$$

where, $\overline{u}\overline{q}$ is the background advection term representing the climatological monsoon moisture transport; $u'\overline{q}$ is the wind-anomaly term, describing the redistribution of climatological moisture by wave-induced circulation anomalies; $\overline{u}q'$ is the moisture-anomaly term, characterizing the advection of humidity anomalies by the mean monsoon flow; and $u'q'$ the transient eddy term that quantifies the covariance between wind and humidity anomalies. A residual term is also computed to assess the numerical closure of the decomposition, but it remains negligible throughout the analysis. The moisture budget is evaluated at 850 hPa, a level widely recognized as representative of the core monsoon flow and low-level moisture transport over West Africa [18] [19].

To further investigate the mechanisms leading to the east-west asymmetry in rainfall transitions, vertical profiles of specific humidity and vertical velocity are constructed for each Kelvin-wave phase. These diagnostics, averaged separately over WWA and EWA, document the evolution of mid-level subsidence, lower-tropospheric moistening, and the vertical structure of dynamical anomalies associated with the wave. In addition, 600 - 850 hPa vertical wind shear is examined to assess whether shear variations contribute to the observed modulation of convection.

Finally, the composite analyses rely on a 44-year dataset (1981-2024), providing substantial sampling for all Kelvin-wave phases. Because the primary objective of the study is mechanistic diagnosis rather than statistical inference, no additional formal significance testing is imposed. Instead, the robustness of the results is evaluated by examining spatial coherence, consistency across diagnostics, and agreement with known Kelvin-wave structures. The terms "*earlier*" and "*sharper*" transitions refer to specific characteristics of the phase-composited rainfall anomalies. For each Kelvin-wave phase, composite anomalies are computed at each grid point using all days belonging to that phase. An *earlier transition* denotes a longitudinal difference in the phase at which rainfall anomalies reverse sign (from positive to negative, or vice versa), with eastern West Africa exhibiting this sign change one to two phases ahead of the western sector. A *sharper transition* refers to a more abrupt change in anomaly magnitude between successive phases, reflected by a larger amplitude difference between adjacent phase composites in the east compared to the west.

3. Results

The composite analysis reveals a clear and coherent modulation of West African rainfall by CCKWs during the monsoon season. **Figure 1** displays the evolution of CHIRPS rainfall anomalies across the eight Kelvin-wave phases. A strong wet anomaly emerges during phase 2, followed by a well-defined dry anomaly in phase 6, marking the canonical convective and suppressed stages of the wave. The transitions surrounding these extrema (phases 3 - 4 for the wet-to-dry sequence and phases 7 - 8 for the dry-to-wet sequence) exhibit a remarkable longitudinal contrast. Eastern West Africa transitions sharply and early during both sequences, whereas western regions show a more gradual and delayed progression between phases. This inherent east-west phasing asymmetry is a central feature of the Kelvin-wave influence.

To assess whether near-surface moisture boundaries contribute to this contrast, **Figure 2** shows the composite position of the ITD compared with its climatological latitude. Across all eight phases, the ITD exhibits minor meridional variations and remains confined within its climatological corridor. This stability echoes the conclusions of [12], confirming that ITD shifts do not accompany the rainfall anomalies and therefore cannot explain the observed longitudinal disparities.

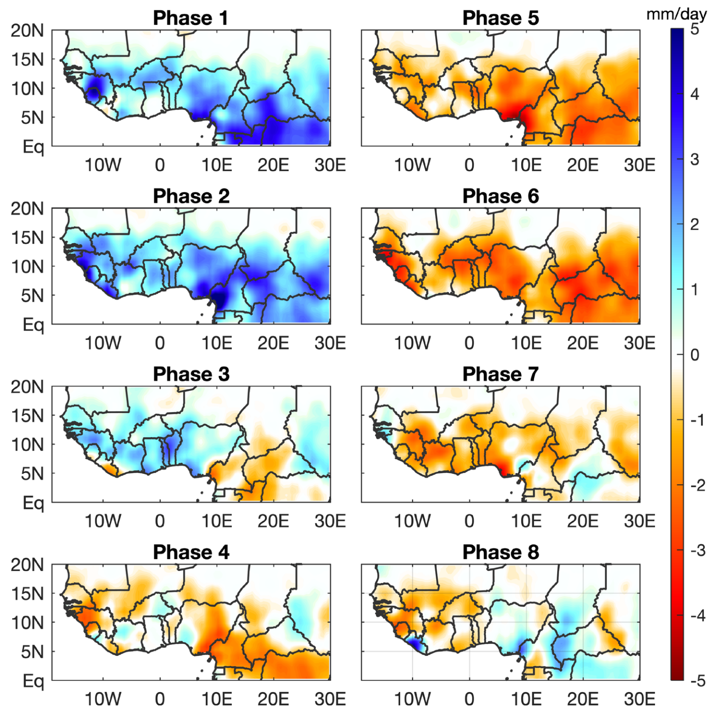

Figure 1. Composite CHIRPS rainfall anomalies (mm·day^{-1}) for the eight Kelvin-wave phases during JAS. Positive values indicate enhanced rainfall and negative values indicate suppressed rainfall. The canonical wet (phase 2) and dry (phase 6) stages, as well as the wet-to-dry (phases 3 - 4) and dry-to-wet (phases 7 - 8) transitions, are clearly visible.

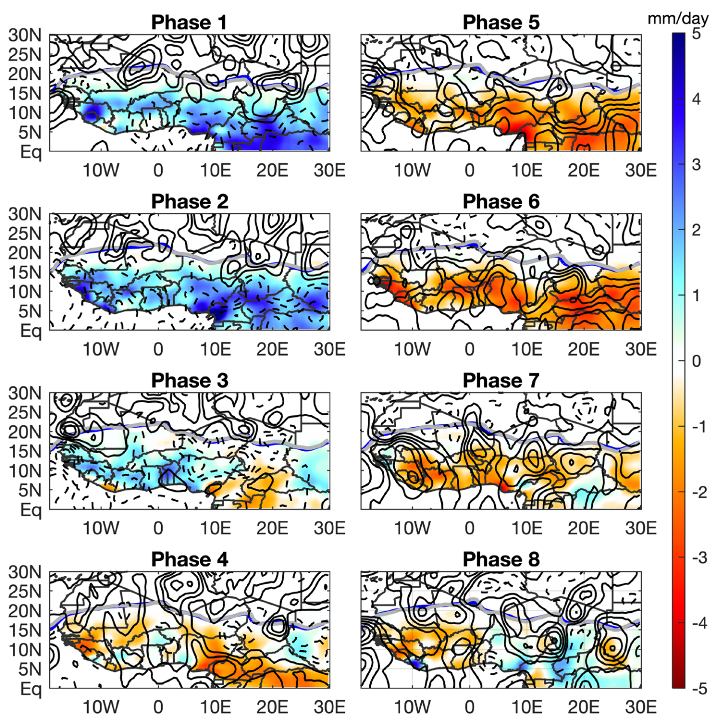

Figure 2. Composite latitude of the Intertropical Discontinuity (ITD) and Vertical wind shear (600 - 850 hPa) anomalies for each Kelvin-wave phase (grey curve), compared to the JAS climatological position (blue curve). The color patterns are the same as in Figure 1.

Figure 2 also presents the modulation of vertical wind shear (600 - 850 hPa) across the wave phases. Consistent with the dynamical footprint of CCKWs, shear weakens during convectively active phases and strengthens during suppressed phases. However, this modulation is broadly uniform across West Africa, showing no coherent east-west differences that could account for the distinct timing of rainfall transitions. The shear response, while dynamically consistent, is therefore not the origin of the asymmetry identified in Figure 1. Additional composite analyses of zonal wind anomalies at 600 hPa and at 200 hPa, representative of the African Easterly Jet (AEJ), and Tropical Easterly Jet (TEJ), do not also reveal significant longitudinal variations across KW phases (not shown).

A more informative perspective emerges from the analysis of horizontal moisture flux. The mean monsoon moisture flux shown in Figure 3 displays the expected southwesterly inflow across the region, with only modest longitudinal differences. This relatively invariant background flow provides the reference against which flux anomalies must be interpreted.

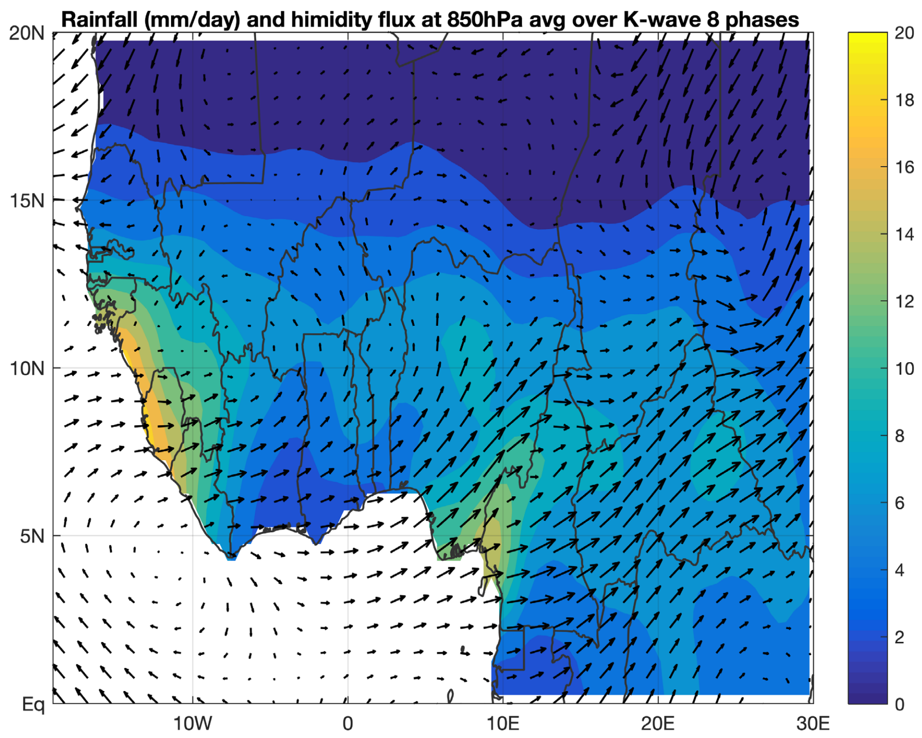

Figure 3. Mean 850-hPa moisture flux vector field $\overline{uq}$ (vectors) and rainfall (color) averaged over all Kelvin-wave phases. The climatological southwesterly monsoon inflow provides the background structure for interpreting flux anomalies.

The flux component associated with the advection of climatological humidity by wind anomalies $u'\overline{q}$) shown in Figure 4, exhibits broad, wave-like structures consistent with Kelvin-wave circulation anomalies. Although these structures modulate the horizontal redirection of the climatological moisture field, they remain too spatially diffuse to account for the sharp east-west contrast in rainfall seen in Figure 1. Their contribution to the asymmetric transitions, therefore, appears secondary.

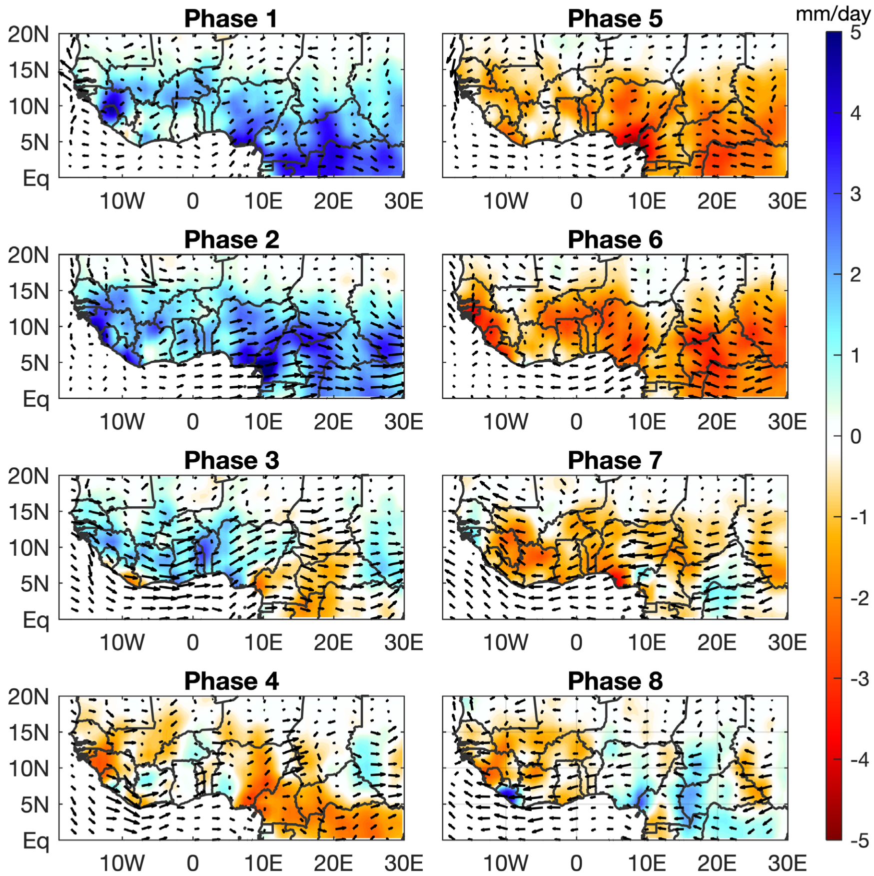

Figure 4. Moisture-flux component $u'\overline{q}$, representing the transport of climatological humidity by wind anomalies. The color patterns are the same as in Figure 1.

In contrast, Figure 5 (representing flux anomalies associated with wind perturbations $u'q'$) highlights a more organized redistribution of moisture, particularly during the transition phases. These anomalies propagate eastward in a manner that reflects the dynamical signature of the Kelvin wave. Yet, despite this coherent structure, the flux magnitudes remain relatively uniform longitudinally and do not match the sharper timing of the rainfall transitions in the east.

The key to understanding the asymmetry lies in Figure 6, which presents the flux component $\overline{u}q'$, representing the transport of humidity anomalies by the mean monsoon flow. Unlike the previous components, this term exhibits strong amplitude differences between eastern and western West Africa, with earlier and more pronounced sign reversals in the east. Importantly, as Figure 3 shows, the mean wind $\overline{u}$ does not substantially change across the region; thus, the structure of $\overline{u}q'$ primarily reflects changes in the humidity anomalies q'. The east-west contrast in this term, therefore, emerges not from differences in horizontal advection efficiency, but from differences in the humidity anomalies themselves.

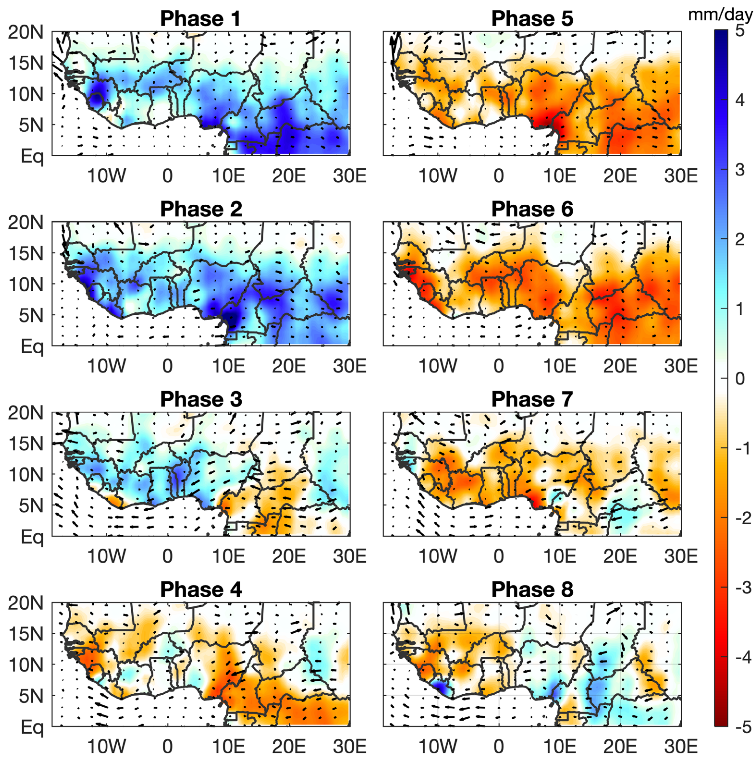

Figure 5. Moisture-flux component $u'q'$, representing the transport of humidity anomalies by wind anomalies. The color patterns are the same as in Figure 1.

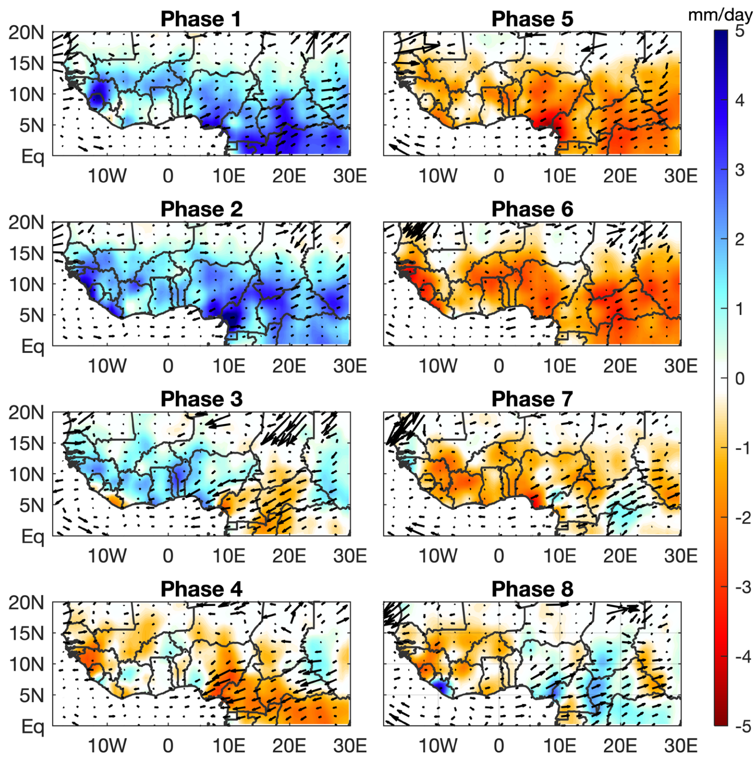

Figure 6. Moisture-flux component $\bar{u}q'$, representing the advection of humidity anomalies by the mean monsoon flow. The color patterns are the same as in Figure 1.

Figure 7 provides the final piece of the mechanism by showing the vertical profiles of humidity and vertical velocity. During the wet-to-dry transition (phases 3 - 4), the eastern sector exhibits deeper and more intense mid-level drying associated with Kelvin-wave subsidence, leading to large negative humidity anomalies q'. These anomalies naturally appear in the flux $\overline{u}q'$ as strong negative contributions, producing the sharper transition in rainfall observed in Figure 1. Conversely, during the dry-to-wet transition (phases 7 - 8), ascending motion and column moistening develop earlier in the east, generating positive humidity anomalies and thus an earlier reversal in the flux sign. Western West Africa, with its weaker vertical response, displays smaller and delayed humidity anomalies, consistent with the more gradual rainfall transitions.

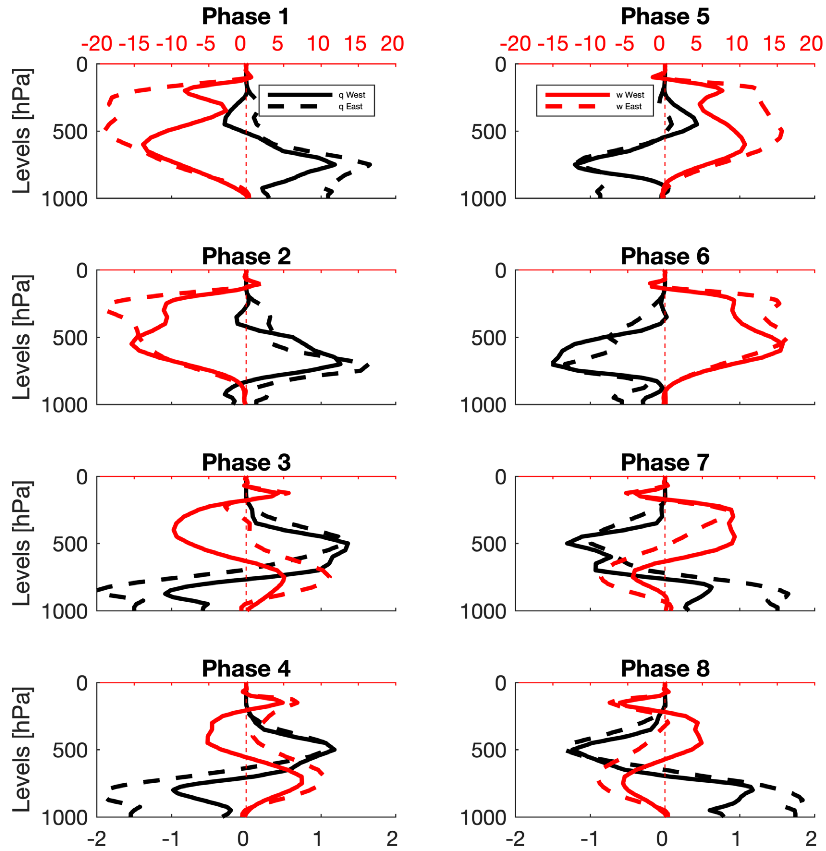

Figure 7. Composite of the vertical profiles of q and w average over the eastern (EWA, 15˚ - 22˚E/0˚ - 10˚N) and western (WWA, 5˚W - 5˚E/5˚ - 15˚N) West Africa.

Together, Figures 1-7 show that the longitudinal asymmetry in Kelvin-wave rainfall modulation arises primarily from differences in the vertical generation of humidity anomalies, not from differences in horizontal moisture transport. The horizontal flux merely redistributes the anomalies that have already been created by vertical dynamical processes, explaining why eastern West Africa, which exhibits a stronger vertical response, transitions earlier and more abruptly between wet and dry phases.

4. Discussion

The results presented in Section 3 reveal that CCKWs exert a strong modulation on West African rainfall during the monsoon season, yet this influence unfolds asymmetrically between eastern and western West Africa. Figure 1 through Figure 7 together provide a coherent dynamical explanation for this longitudinal contrast, linking surface rainfall anomalies to the vertical and horizontal moisture structure of the atmosphere.

Figure 1 establishes the fundamental signature of the Kelvin-wave life cycle on rainfall, with distinct wet (phase 2) and dry (phase 6) anomalies and two transition periods surrounding them. The sharper transitions in eastern West Africa (both the collapse of rainfall during phases 3 - 4 and the early recovery during phases 7 - 8) call for a mechanistic explanation beyond simple propagation effects. Figure 2 and Figure 3 rule out two potential large-scale drivers. The ITD (Figure 2) shows negligible meridional movement across phases, indicating that surface moisture boundaries remain fixed. Vertical wind shear (Figure 2) responds to the Kelvin wave, weakening during convective phases and strengthening during suppressed phases, but it does so uniformly across West Africa, offering no longitudinal differentiation.

The horizontal moisture flux analysis in Figures 3 through 6 provides the first indication of a deeper dynamical asymmetry. The background monsoon flux (Figure 3) shows a stable southwesterly inflow across both eastern and western regions. This stability implies that the mean flow itself cannot account for the regional contrast in rainfall transitions. Flux anomalies associated with wind perturbations (Figure 5) and with the transport of background humidity by anomalous winds (Figure 4) display the expected Kelvin-wave circulation signature, yet their spatial distribution remains broadly similar across longitudes. Neither component captures the timing differences evident in rainfall.

The decisive insight emerges in Figure 6, which isolates the flux component $\bar{u}q'$: the advection of humidity anomalies by the mean monsoon flow. This term exhibits earlier and more intense sign reversals in eastern West Africa, matching the rainfall transitions seen in Figure 1. However, since the mean flow $\bar{u}$ shows no significant longitudinal variation (Figure 3), the structure of $\bar{u}q'$ must arise from differences in the humidity anomalies q' themselves and not from differences in horizontal advection efficiency.

Figure 7 provides compelling confirmation of this interpretation by revealing strong longitudinal differences in vertical humidity structure. During the wet-to-dry transition (phases 3 - 4), the eastern sector experiences much deeper and stronger mid-level drying than the western West Africa, driven by Kelvin-wave subsidence. This drying produces large negative humidity anomalies q', which in turn generate strong negative flux contributions in $\bar{u}q'$ (Figure 6), leading to the rapid collapse of rainfall observed in Figure 1. During the dry-to-wet transition (phases 7 - 8), ascending motion and moistening develop earlier in the east, producing positive humidity anomalies and driving an earlier flux reversal. Western West Africa, by comparison, exhibits weaker vertical motion anomalies and more subdued humidity changes, consistent with its slower rainfall transitions.

Taken together, **Figures 1-7** converge toward a single coherent physical mechanism: the east-west asymmetry arises from differences in the vertical generation of humidity anomalies by Kelvin-wave-induced vertical motions. The horizontal moisture flux simply redistributes these anomalies, whose sign and magnitude have already been set by vertical processes. Eastern West Africa, which experiences deeper and stronger subsidence and ascent, produces larger humidity anomalies and therefore exhibits sharper transitions in rainfall. Western regions, with a more muted vertical response, produce weaker anomalies and thus transition more gradually.

These findings refine our understanding of Kelvin-wave influences over Africa and complement earlier work such as [12], [17], and [13]. While the latter highlighted the importance of tropical waves for modulating rainfall and extreme events, the present study demonstrates that the local expression of Kelvin-wave impacts is fundamentally shaped by how regional atmospheric columns respond vertically, not merely by the passage of the wave itself.

The implications for predictability are significant. Kelvin waves propagate coherently from the Indian Ocean, offering one of the few reliable subseasonal signals in the tropics. However, their rainfall impacts will vary spatially depending on the background vertical structure of the monsoon environment. This means that subseasonal prediction systems must account not only for wave detection and tracking but also for regional differences in vertical humidity sensitivity if they are to reproduce the timing and magnitude of rainfall transitions across the West Africa.

5. Conclusions

This study provides a comprehensive assessment of how CCKWs modulate rainfall over the West Africa during the monsoon season and explains why these impacts unfold asymmetrically between eastern and western West Africa. By combining daily rainfall observations, convection proxies, and ERA5 reanalysis data, and by examining the Kelvin-wave life cycle through composite analysis, the study reveals a clear longitudinal contrast in the timing and intensity of rainfall transitions. As shown in **Figure 1**, Eastern West Africa exhibits sharper and earlier transitions between wet and dry phases, while western regions respond more gradually.

The analyses demonstrate that this asymmetry cannot be attributed to surface moisture boundaries or mesoscale-modulating factors. The position of the ITD remains largely unchanged across wave phases (**Figure 2**), and vertical wind-shear anomalies evolve similarly across the region (**Figure 2**), indicating that these large-scale features do not dictate the observed differences in rainfall response.

Instead, the key lies in how Kelvin-wave dynamics restructure atmospheric humidity. The mean monsoon wind (**Figure 3**) exhibits little longitudinal variation, implying that differences in horizontal moisture transport do not originate from changes in the background flow. Anomalous flux components associated with wind perturbations (Figure 5) and with the transport of background humidity (Figure 4) reflect the wave's large-scale circulation but do not reproduce the contrasting timing of rainfall transitions.

The decisive contribution emerges from the flux term representing the horizontal transport of humidity anomalies by the mean monsoon flow (Figure 6). Because the mean wind is nearly uniform across longitudes, the spatial structure of this term reflects differences in humidity anomalies q', not differences in advection efficiency. These humidity anomalies are generated vertically, as shown by the profiles in Figure 7. During the wet-to-dry transition, the eastern West Africa undergoes deeper and more intense mid-level drying due to Kelvin-wave-induced subsidence, producing strong negative humidity anomalies. These anomalies are then transported by the background monsoon flow, leading to rapid suppression of convection and the abrupt rainfall transition in the east. During the dry-to-wet transition, the earlier onset of ascent and moistening in the east produces positive humidity anomalies that translate into an earlier reactivation of rainfall.

This integrated vertical-horizontal mechanism provides a unified explanation for the longitudinal asymmetry in Kelvin-wave impacts. The horizontal flux redistributes anomalies that originate from vertical processes, and the strength of those vertical processes differs between eastern and western West Africa. Eastern regions, exhibiting a stronger vertical dynamical response, produce larger and earlier humidity anomalies, while western regions experience weaker perturbations and thus transition more slowly.

These findings offer new insight into the interaction between CCKWs and the West African monsoon. They underscore that the impact of Kelvin waves is not uniform across West Africa but depends critically on how local atmospheric columns respond to wave-induced vertical motions. This has important implications for subseasonal prediction: models must not only detect and propagate Kelvin-wave signals but also realistically simulate the regional vertical structure of humidity and vertical motion if they are to capture the timing and amplitude of rainfall transitions.

Despite these robust signals, the interpretation of the results should be viewed in light of the methodological framework adopted in this study. Future work should explore how well current climate and weather prediction models represent the vertical response of humidity to Kelvin-wave forcing and whether convection-permitting simulations can capture the regional variations identified here. It should also be noted that this study relies primarily on composite analysis, which emphasizes the mean Kelvin-wave signal but may obscure variability among individual CCKW events. Differences in wave amplitude, propagation speed, or interaction with the background monsoon state may lead to case-to-case variability that is not fully captured by phase composites. Complementary event-based analyses would therefore be valuable to further document this variability and assess the robustness of the proposed mechanisms. Additionally, examining the interaction of Kelvin waves with other tropical modes such as equatorial Rossby waves, TD-type disturbances, and the MJO would help build a more integrated understanding of multiscale rainfall variability over West Africa.

Acknowledgements

Dr. Diakhaté gratefully acknowledges Professor Douglas Parker of the University of Leeds for his scientific support. The author also expresses appreciation to the *Université Amadou Mahtar Mbow* (*UAM*) and the *Laboratoire de Physique de l'Atmosphère et de l'Ocean-Siméon Fongang* (*LPAO-SF*) for providing an enabling academic environment and institutional support for climate research activities. The analysis benefited from the support of the AMMA-2050 project and from freely available datasets, including CHIRPS precipitation from the Climate Hazards Group, outgoing longwave radiation from NOAA, and atmospheric reanalysis fields from the ECMWF ERA5 archive, whose efforts in maintaining open-access climate data are sincerely acknowledged.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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